ARMY RESEARCH LABORATORY

Impact Seeded Fault Data of Helicopter Oil Cooler Fan Bearings

by Canh Ly

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Impact Seeded Fault Data of Helicopter Oil Cooler Fan Bearings

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Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT

This report documents the seeded fault data for oil cooler fan bearings from the Impact Technologies, LLC, as part of the Air Vehicle Diagnostic and Prognostic Improvement Program (AVDPIP). AVDPIP is a three-year collaborative agreement between Impact Technologies, LLC, the Georgia Institute of Technology, and the U.S. Army Research Laboratory (ARL). In this report, we outline a procedure to extract the data and present examples showing how to obtain a specific set of data.

15. SUBJECT TERMS

AVDPIP, oil cooler fan bearings, fault

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1. Introduction

Impact Technologies, LLC, has now completed the Air Vehicle Diagnostic and Prognostic Improvement Program (AVDPIP), which was a three-year collaborative agreement between Impact Technologies, LLC, the Georgia Institute of Technology, and the U.S. Army Research Laboratory (ARL) under the Army contract number W911NF-07-2-0075. The main objective of the three-year program (*1*) was to develop, test, and evaluate open systems software modules that would enhance the Army's current fault diagnosis capabilities, as well as provided failure prognosis maturation for critical Army aircraft components and support the Army's Condition-Based Maintenance Plus (CBM+) goals. The first year was the base period of the performance. The objective of the base period of the AVDPIP effort was to use configuration, usage, maintenance, monitoring, and baseline and fault data provided by the Army to develop diagnostic and prognostic algorithms for a fault-prone helicopter component, namely, an oil cooler bearing of UH-60 helicopter. This bearing was selected among many other components of the UH-60 helicopter.

The second year efforts, designated as *Option Phase I* [Report W911NF-07-2-0075_Impact_Opt1QR3_P813_30Nov2009] (*2*), were to expand on the developments of the base period of performance and prepare to implement their plan in support of the Army's helicopter health monitoring.

The third year efforts, designated as *Option Phase II*, [Report W911NF-07-2-0075_Impact_Opt2_QR2_P813_01Mar2010] (*3*) included (1) integrating technical developments of the AVDPIP program into a modular software suite for CBM analysis of Army aircraft components, (2) demonstrating the extensively and compatibility of developments, and incorporating Army data and feedback into the final software releases and reports, and (3) carrying out algorithm performance assessments and quality tests.

In the efforts to accomplish all the goals for the program, Impact Technologies, LLC, designed and built a test rig, shown in figure 1. The top view of the test rig is shown in figure 2, which allowed for simultaneous test runs of up to four bearings in separate test cells. These test cells were labeled Test Cell 1, Test Cell 2, Test Cell 3, and Test Cell 4.
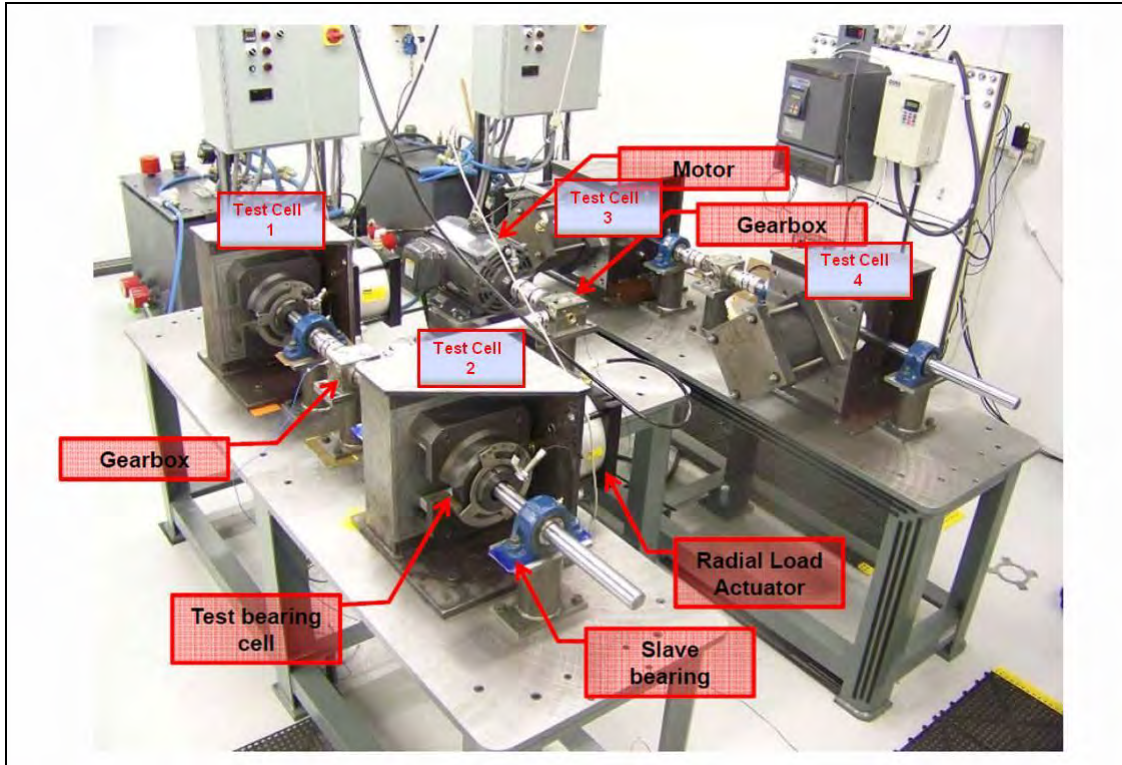
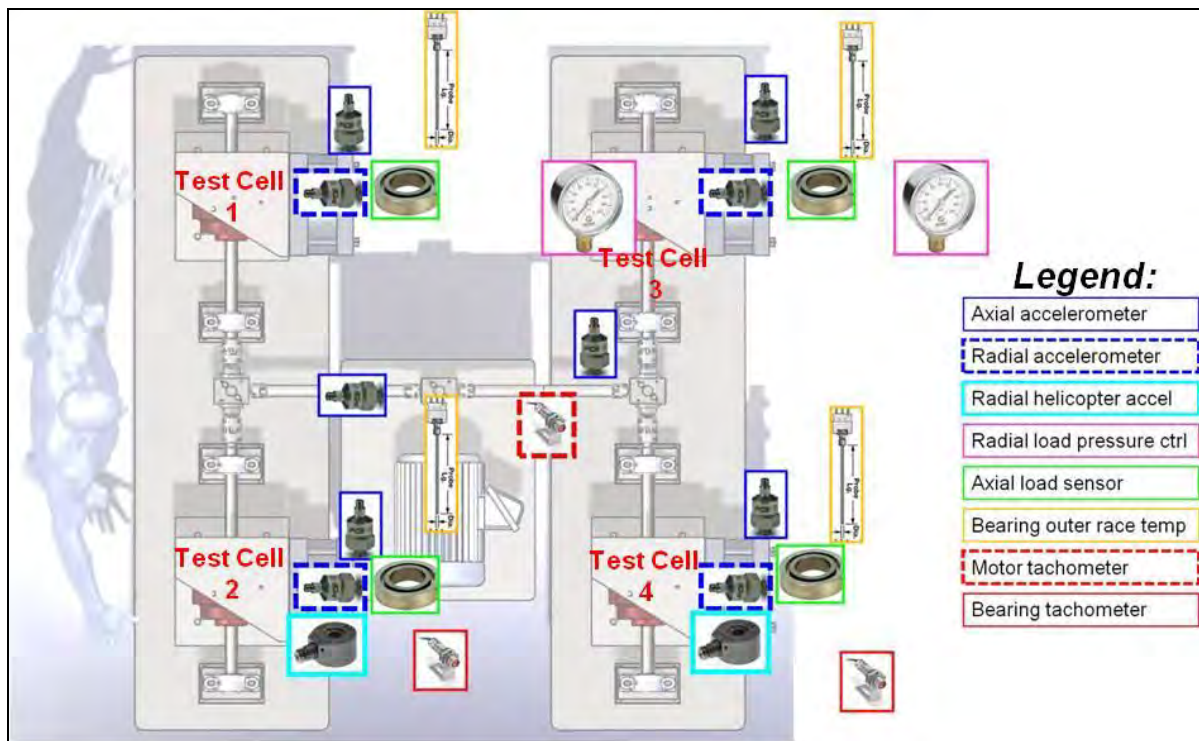Figure 1. Oil-cooler bearing test-rig (photo from Impact Technologies, LLC.).

Figure 2. Top view drawing of the test rig, showing the locations of the test cells, accelerometers, and sensors.

The test rig provides the ability to perform accelerated fatigue damage progression with controlled/known conditions (independent variables), as shown in table 1.

Table 1. Independent/controlled variables of planned oil cooler bearing seeded fault tests.

Variables	Values	Notes
Bearing type	H-60 oil cooler bearings	Other Equipment Manufacturer (OEM) (MRC Company), Part No. 210SFFC
Speed	4100 RPM	Manufacture limits max speed to 4500 RPM
Load	Overload considered 3000 lb axial 5000 lb radial	The field bearings are not believed to have high loads, but we performed accelerate degradation to test multiples bearings to gain statistical relevance and extrapolate results to scale for field conditions.
Temperature	Constant	Ambient/controlled lab environment
Humidity	Ambient	Expected to have a minimal effect because of the relative short duration of the test and the constant presence/regular changing of the grease
Corrosion	Several levels: None, mild, medium, severe	The initial level of corrosion is a seeded fault. The levels are named as Corrosion Level 0 (none), 1 (mild), 2 (medium or moderate), and 3 (severe).

The geometric parameters for the oil cooler helicopter bearing used in the test rig are listed in table 2.

Table 2. Oil cooler bearing geometry parameters.

Bearing Geometry Parameter	
# of Rolling Elements	10
Ball Diameter (mm)	12.7
Pitch Diameter (mm)	70
Contant Angle (radian)	0

Each test cell of the test rig consists of a radial and axial accelerometer, a load cell to measure the axial load, pneumatic regulators to monitor the radial load, thermocouples attached on the bearing raceways, and a tachometer signal to provide a measure of the shaft speed. Data were acquired using a National Instruments-based PXI system; the vibration data were sampled at a rate of 102.4 KHz. The signals were acquired from accelerometers mounted at different locations, shown in figure 2, corresponding to a variety of operating conditions (loads, speeds, etc.) and different damage conditions (levels 0, 1, 2, and 3, as described in section 2). Each data file consisted of 102,400 samples, which provided a sampling time of 1 s for each data file and a frequency resolution of 1 Hz for spectrum analysis.

The seeded fault data were delivered to ARL in a 1.5-TB Western Digital hard drive. The data in the hard drive were categorized into two types of data: baseline and progression. In this report, a procedure to extract the data is outlined. In particular, the extraction of the baseline and progression data is highlighted.

2. Types of Seeded Fault Data

Impact Technologies conducted an experimental data collection for oil cooler helicopter bearings. The procedure for testing the bearings is as follows.

The bearings were tested in the test rig one or more times. Each "test run" was delimited by test rig stops. During a test run, the bearings can experience different radial loads and shaft speeds. For more information on the bearing test run preparation and completion overview, see the *Final Report for Option Phase II*, (*4*) under the contract number W911NF-07-2-0075, dated on September 10, 2010, prepared by Romano Patrick.

To make this report a standalone document, the following information was captured from the final report (*4*) as indicated. There were three preparation and completion steps taken during the bearing testing: (1) Select the appropriate test specimen, (2) load the test specimen, and (3) test the specimen. "Specimen" indicates the bearing under test.

There were two stages of testing for each bearing: damage detection and damage progression. The damage detection stage started with fault seeding and bearing operation until the behavior of the damaged bearing could be distinguished from that of the different initial conditions tested. This testing stage involved short runs (approximately 40–45 min in duration) of the bearings to measure stable vibration signals—the "baseline test" for the different fault conditions tested. The test conditions tested were those of "healthy" bearings (i.e., brand-new bearings) and corroded bearings with three different degrees of corrosion.

The tests involved long runs (approximately 1 to 4 h) of the corroded bearing—a "progression test." The progression tests focused on staying at max speed (4500 RPM) and force for long periods of time to see how the bearing degraded under heavy load. All corrosion sets of bearings were corroded under temperature/humidity conditions by IMR Test Labs (NY) to achieve a degree of corrosion that was compared with reference samples. The reference samples were thus used a guide for the level of corrosion in the test specimens (specimen). The reference samples consist of retired parts provided by the Army Aviation Engineering Directorate (AED), particularly, two specimens referred to as the 874[*] and 506[†] bearings. The corrosion levels were established as follows:

- Corrosion Level 0: No corrosion, considered as a brand-new bearing

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[*] The original specimens were removed in September 2004, from the helicopter fleet with tail numbers ending in 847 per Vibration Management Enhancement Program (VMEP) vibration indicators exceeding the allowable threshold.

[†] The original specimens were removed September 6, 2005, from the helicopter fleet with tail numbers ending in 506 per Integrated Mechanical Diagnostic Health and Usage Monitoring System (IMD HUMS) vibration indicators suggesting a fault.

- Corrosion Level 1: Corrosion is about half as intense as that of the reference samples. Upon daily visual inspection, it was determined that after four days of active corrosion in the chamber, corrosion level 1 had been reached.

- Corrosion Level 2: Corrosion intensity is about the same as that of the reference samples. Corrosion level 2 was achieved after eight days of active corrosion in the chamber.

- Corrosion Level 3: Corrosion intensity is about twice as that of the reference conditions. Since bearings with corrosion levels 1 and 2 had depicted acceptable corrosion levels after four and eight days, respectively, it was decided to pursue a linear scale for the corrosion days, thus calling for the corrosion level 3 to be defined as 12 days of active corrosion in the chamber.

All the test runs started with zero radial load force applied. When the application of radial force was required by the test, the bearing was first spun without the load. As spinning and temperature were stable, the load was gradually increased in steps until the desired load was reached. The load was applied in steps, not as a ramp, as shown in figure 3, which depicts an example of Tests 15 and 16.
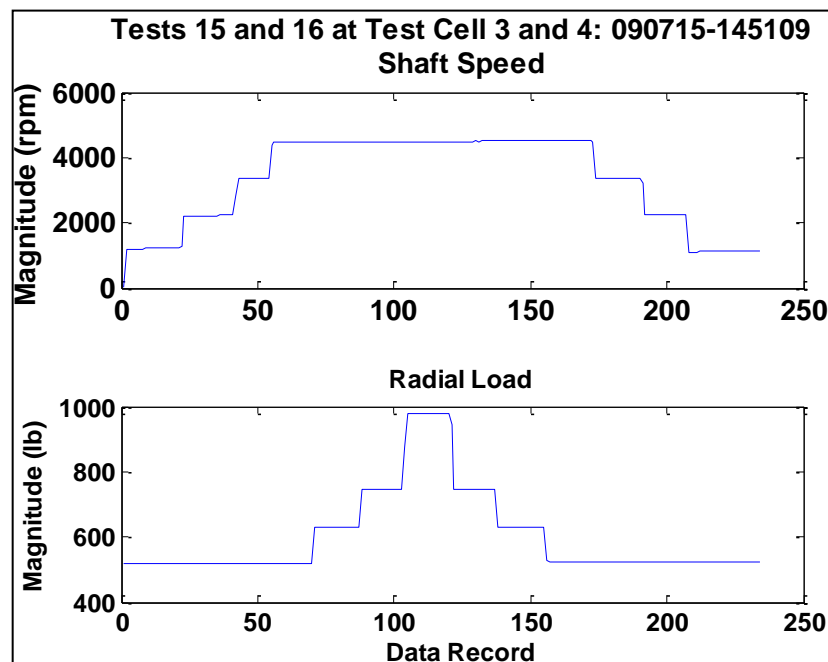

Figure 3. Test operating conditions.

The test runs were performed sequentially until there was a change in the test bearing's condition that would warrant inspection. When an inspection was needed or the testing specimen was completed, the rig was disassembled. Cleaning of the bearing was done as follows:

- The test specimen was first removed from the test rig.

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- The specimen was washed in a parts washer, and then rinsed with water.

- Compressed air was run through the test specimen to ensure it was dried properly.

- The specimen was visually inspected to ensure there was no remaining grease or liquid deposits in the raceways.

- Each inner and outer race was cleaned with a cotton swab to remove any remaining grease.

The testing on bearings continued until there was a noticeable change in its condition. Common conditions that warranted stopping the testing of a specimen included:

- Large spall on the raceway (inner or outer race)

- Long test time with minimal progression

- Damaged specimen (e.g., burnt grease on the raceway)

3. Test Matrix for Oil Cooling Bearing Data Collection

Table 3 shows the complete test matrix of the seeded fault data collected from the test rig for the two types of data: baseline and progression. The baseline data are test numbers 9–16, 25–34, and 40. Test numbers 9 and 10 in the baseline data set 1 were recorded to check out all the hardware, including the bearings, shaft, motor, etc. The progression data are test numbers 23–24, 35–39, and 41–43. Throughout the report, we refer to the data using the test number as indicated in the Test No. column, bearing number as indicated in the Specimen ID column, test cell, and corrosion as indicated in the Corrosion Level column. All other columns will be explored in another report.

As noted under Test ID, there are different types of test data, S-, T-, -V, and -P. The first S- (highlighted in yellow) indicates the initial test setup to collect the data for the first run tests. These data files are not recorded in the hard drive. The second S- (highlighted in blue) indicates special tests that were used for the demonstration when ARL (Sensors and Electron Devices Directorate [SEDD] and Vehicle Technology Directorate [VTD]) visited the Impact Technology, LLC, in Rochester, NY, in October 2009. The data set with a –T represents the regular tests. The –V data set represents the vibration baseline data. The -P data set (in the blue sections) represents the vibration data from the damage progression tests.

There are two numbers under the Specimen ID. The first number is the corrosion level number. The second number followed by a dash (—) indicates the batch of bearings being under test. For instance, looking at test number 11 of the baseline 1 section in the table, the bearing number is 2-2, i.e., the bearing is specified at the corrosion level 2 for batch 2.

Table 3. Test matrix of seeded fault data.

		Test No.	Test ID	Specimen ID	Test type	Test Cell	Inspection stops?	Test Group	Ring pair	Disassembly for corrosion?	Corrosion	Test purpose	Test Date	Total Test Time (approx hrs)
Initial Set-Up	Safety test / rig test	1	S-1-V	0-1	Vib baseline	1	N	S-1	24	Y	0	Safety / configuration test	6/30/2009	0.73
		2	S-2-V	3-1	Vib baseline	2	N	S-2	3	Y	3	"	6/30/2009	
	Safety test / rig test	3	S-1-V	0-1	Vib baseline	3	N	S-1	24	Y	0	"	7/6/2009	0.68
		4	S-2-V	3-1	Vib baseline	4	N	S-2	3	Y	3	"	7/6/2009	
Baseline 1	Corrosion Effect Round 1	9	T-1-V	0-2	Vib baseline	1	N	T-1	4	Y	0	Round 1 of tests for characterization of vibration vs. corrosion level	7/6/2009	0.68
		10	T-4-V	1-1	Vib baseline	2	N	T-4	16	Y	1	"	7/6/2009	
		11	T-3-V	2-2	Vib baseline	3	N	T-3	12	Y	2	"	7/9/2009	0.7
		12	T-2-V	3-2	Vib baseline	4	N	T-2	7	Y	3	"	7/9/2009	
Baseline 2	Corrosion Effect Round 2	13	T-1-V	0-3	Vib baseline	1	N	T-1	5	Y	0	Round 2 of tests for characterization of vibration vs. corrosion level	7/9/2009	0.63
		14	T-4-V	1-3	Vib baseline	2	N	T-4	18	Y	1	"	7/9/2009	
		15	T-3-V	2-3	Vib baseline	3	N	T-3	13	Y	2	"	7/15/2009	0.68
		16	T-2-V	3-3	Vib baseline	4	N	T-2	8	Y	3	"	7/15/2009	
Progression 1	Progression	23	T-2-P	3-2	Progression	1	Y	T-2	7	Y	3	Damage progression Test	Start Date: 7/22/2009	14.62
		24	T-2-P	3-3	Progression	2	Y	T-2	8	Y	3	"	Start Date: 7/22/2009	
Baseline 3	Secondary Baseline Testing	25	T-1-V	0-2	Vib baseline	1	N	T-1	4	Y	0	Second Round of Vibration Testing	8/28/2009 - 8/31/2009	1.25
		26	T-4-V	1-1	Vib baseline	2	N	T-4	16	Y	1	"	8/31/2009	1.53
		27	T-3-V	2-2	Vib baseline	1	N	T-3	12	Y	2	"	9/2/2009	1.23
		28	T-1-V	0-3	Vib baseline	2	N	T-1	5	Y	0	"	9/2/2009	1.25
		29	T-2-V	3-4	Vib baseline	1	N	T-2	9	Y	3	"	9/9/2009 - 9/10/2009	1.61
		30	T-2-V	3-5	Vib baseline	2	N	T-2	11	Y	3	"	9/9/2009 - 9/10/2009	2.25
		31	T-4-V	1-3	Vib baseline	1	N	T-4	18	Y	1	"	9/14/2009 - 9/16/2009	2.5
		32	T-3-V	2-3	Vib baseline	2	N	T-3	13	Y	2	"	9/11/2009 - 9/16/2009	2.31

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Table 4. Test matrix of seeded fault data (continued).

		Test No.	Test ID	Specimen ID	Test type	Test Cell	Inspection stops?	Test Group	Ring pair	Disassembly for corrosion?	Corrosion	Test purpose	Test Date	Total Test Time (approx hrs)
		33	T-3-V	2-2	Vib baseline	1	N	T-3	12	Y	2	"	9/21/2009	0.66
		34	T-2-V	3-4	Vib baseline	2	N	T-2	9	Y	3			
Progression 2	Progression	35	T-3-P	2-2	Progression	1	Y	T-3	12	Y	2	Damage progression Test	9/21/2009-9/24/2009	3.13
		36	T-2-P	3-4	Progression	2	Y	T-2	9	Y	3	"	9/21/2009-9/24/2009	
		37	S-1-P	0-1	Progression	2	Y	S-1	24	Y	0	"	10/01/2009-10/9/2009	14.1
		35	T-3-P	2-2	Progression	1	Y	T-3	12	Y	2	"	10/01/2009-10/12/2009	
		38	T-2-P	3-5	Progression	1	Y	T-2	11	Y	3	"	10/12/2009-10/16/2009	16.3
		37	S-1-P	0-1	Progression	2	Y	S-1	24	Y	0	"	10/12/2009-10/16/2009	
		37	S-1-P	0-1	Progression	2	Y	S-1	24	Y	0	Damage Progression Demonstration	10/19/2009-10/28/2009	17.9
		35	T-3-P	2-2	Progression	1	Y	T-3	12	Y	2	Damage Progression Demonstration	10/19/2009-10/28/2009	
		39	T-5a-P	3-6	Progression	1	Y	T-5a	20	Y	3	Damage Progression Test	11/10/2009-12/01/2009	28.42
		37	S-1-P	0-1	Progression	2	Y	S-1	24	Y	0	"	11/10/2009-12/01/2009	
Tail 506	Baseline	40	T-5b-V	506	Vib baseline		N	T-5b	21	Y	3	Baseline Vibration Test	12/09/2009-12/14/2009	3.18
Progression 2	Progression	37	S-1-P	0-1	Progression	1	Y	S-1	24	Y	0	Damage progression Test	12/15/2009-12/16/2009	4
		41	T-5b-P	506	Progression	2	Y	T-5b	21	Y	3	"	12/15/2009-12/16/2009	
		42	T-3-P	1-4*	Progression	2	Y	T-3	14	Y	2	"	12/21/2009-	
		43	T-4-P	2-4*	Progression	1	Y	T-4	19	Y	1	"	12/21/2009-	

*A correction was made due to a typo error in the original test matrix file, according to the information sent from the Impact Technologies, LLC, in a DVD dated on May 25, 2010.

4. Data Organization

The data set was organized as follows.

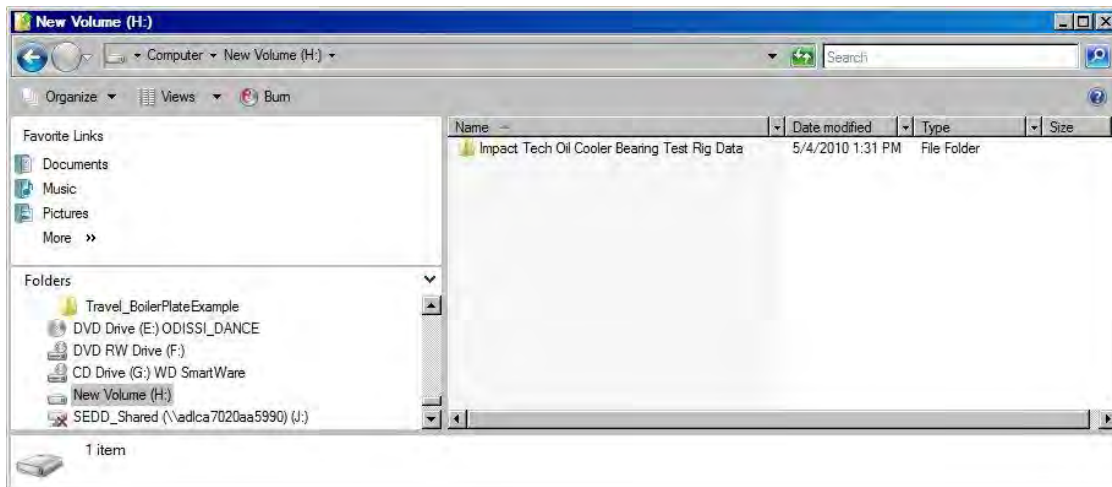Figure 4 shows the top level of the data set in the hard drive.

Figure 4. Top level of the data set.

The second level of the structure is shown in figure 5.
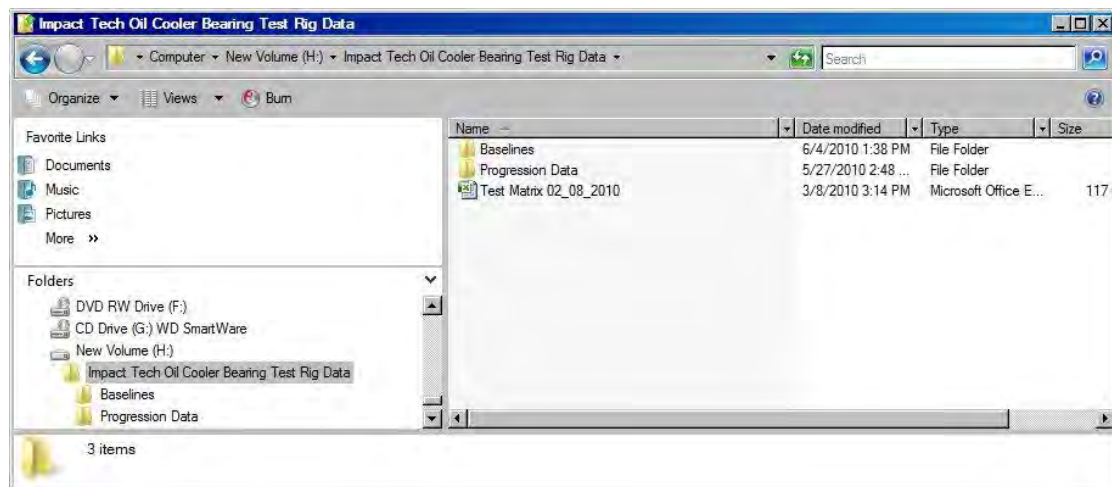

Figure 5. The second level of the data set.

At this level of the data structure, there are two directories—baseline and progression data—and a test matrix file.

The Baselines folder contains test numbers 9–16 and 25–34, and 40 subfolders, as shown in figure 6. The Test Logs folder includes the description of the tests.
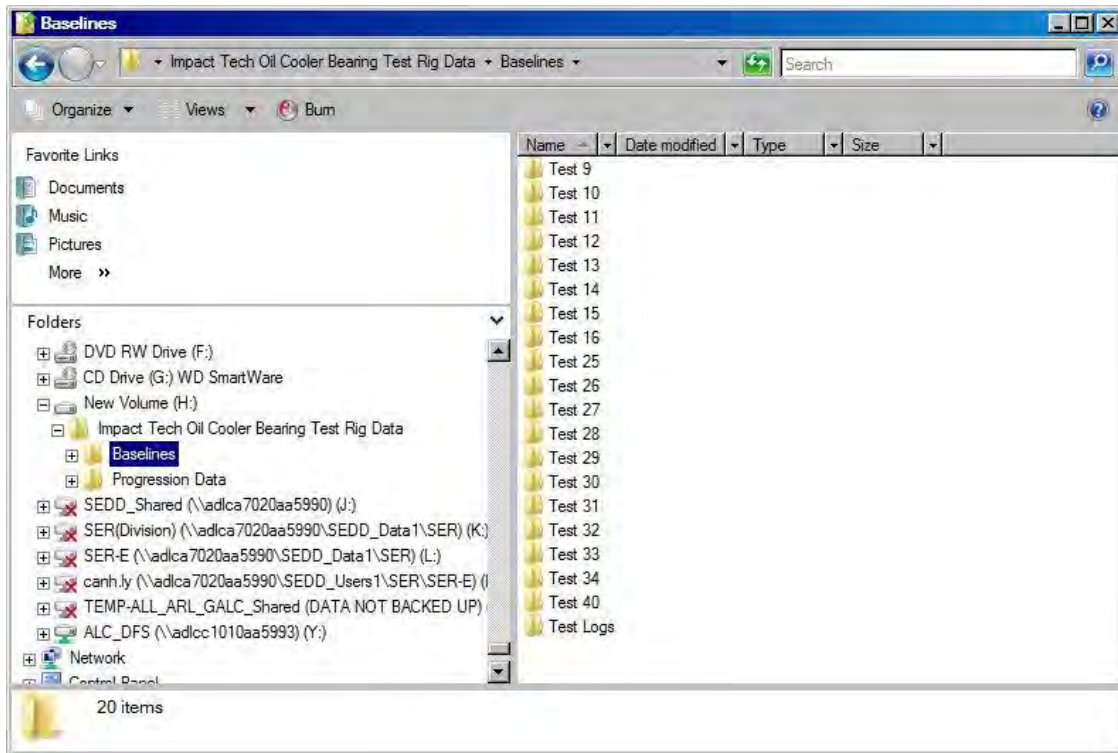
Figure 6. Test numbers in Baselines folder.

Table 4 shows the number of files of each subfolder in the Baseline folder.

Table 5. Baseline test data subfolders.

Test Subfolder	Number of Files
Test 09	1283
Test 10	1283
Test 11	1258
Test 12	1258
Test 13	1244
Test 14	1244
Test 15	1196
Test 16	1196
Test 25	3915
Test 26	3778
Test 27	3336
Test 28	3473
Test 29	3981
Test 30	3981
Test 31	5120
Test 32	5120
Test 33	1157
Test 34	1157
Test 40	1471

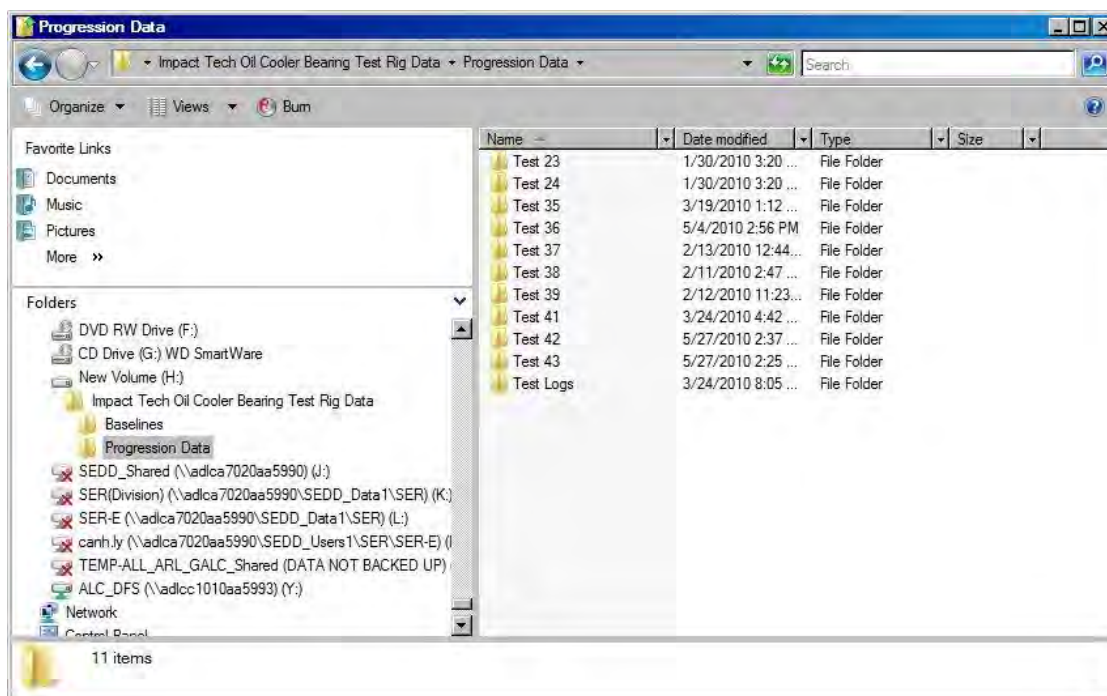The Progression Data folder contains tests numbers 23, 24, 35–39, 41, 42, and 43, as shown in figure 7.

Figure 7. Test numbers in Progression folder.

Table 5 shows all data files in each Test subfolder of the Progression folder. There were two progression tests (Test 35 and Test 42) that led to the inner race faults, as indicated by Impact Technologies, LLC. Other tests are likely to lead other types of faults; however, the faults were not categorized as any type of known faults, such as inner race spall, outer race spall, raceway fault, ball fault, or a combination of those faults.

Table 6. Progression test data subfolders.

Test Subfolder	Number of Files
Test 23	25787
Test 24	25787
Test 35	35741
Test 36	5397
Test 37	107718
Test 38	28292
Test 39	47695
Test 41	1387
Test 42	9366
Test 43	9366

The naming convention for each data file, regardless of being baseline or progression data, is as follows: `4462-090922_095300_second_1.mat`. The first four digits indicate the test number following by a hyphen. The next six digits are the date stamp, followed by an

underscore. In this example, 090922_ means September 22, 2009. The next six digits are time stamp followed by an underscore. In this example, 095300_ means at 9 o'clock, 53 min, and 00 s (09:53:00). Then final part, second_1, means the data were extracted in the first second.

Each data file was stored in the MATLAB™ matrix format. Figure 8 shows an example of the content of each data file.

Figure 8. Content of each data file.

For the purposes of demonstration, we access the vibration data of the axial and radial components from a data file. The axial and radial vibration data were acquired from axial and radial accelerometers, respectively. These accelerometers are shown in figure 2.

In figure 9, axial is the MATLAB structure data type containing Data, NumClippedPts, Bias, Range, RandomAnomally, SensorHealth, and Load.

Figure 9. Content of the axial data structure.

The radial data structure has the same information as the axial structure.

5.   Examples of Axial and Radial Vibration Data

There are two ways to access a data file. First, one can go to a specific Test folder, e.g., Test 35 folder. Then, in the MATLAB Command window at the prompt >>, one can type load [selected filename]. For example, one would use the following command to open a file in the Test 35 folder (assuming that the file is in the current directory path):

```
>>load '4462-091001_144451_second_1.mat'
```

Once the command is executed, the content of the data file is shown (figure 10).
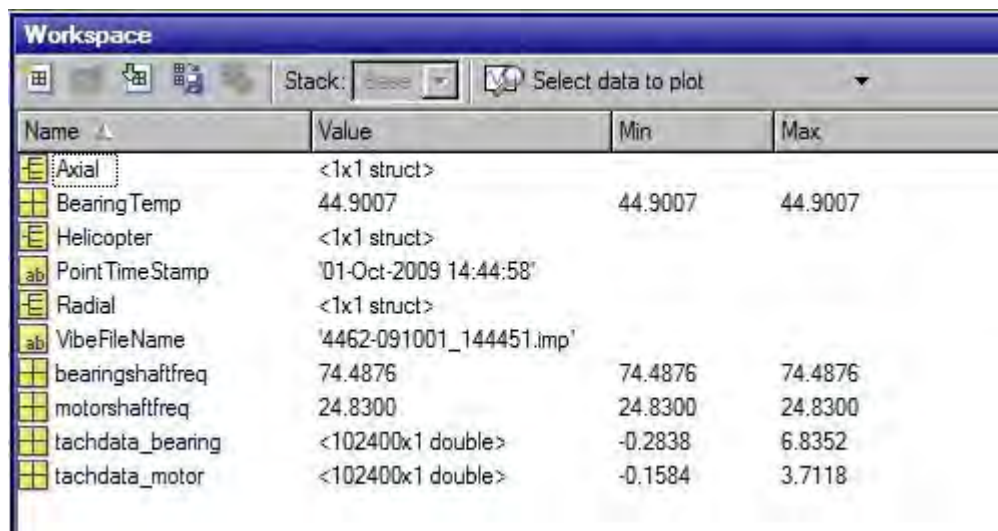

Figure 10. Workspace information of a typical data file.

This screen verifies that the file was open correctly. In this example, the data were collected on October 1, 2009, at 14:44:58 as shown PointTimeStamp variable in the workspace. Note that there was a time delay between when the data was collected and when it was recorded by the collection system. The filename shows an 11:44:51 time, but the PointTimeStamp shows 14:44:58.

One can plot the axial raw data from the loaded file as follows:

```
>> plot(Axial.Data)
>> xlabel('Number of Samples')
>> ylabel('Amplitude (g)')
>> title('Axial Data')
>> grid
```

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Figure 11 shows the axial raw data. The number of samples of the data file is 102400, or equivalent to a 1-s data length.
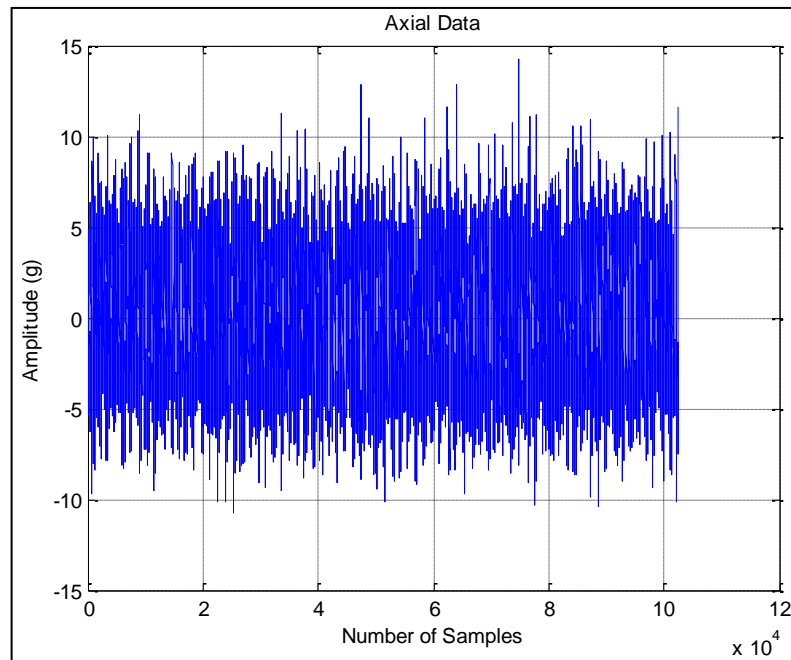

Figure 11. Axial raw data.

Similarly, figure 12 shows the radial raw data plotted using the following commands:

```
>> plot(Radial.Data)
>> xlabel('Number of Samples')
>> ylabel('Amplitude (g)')
>> title('Radial Data')
>> grid
```
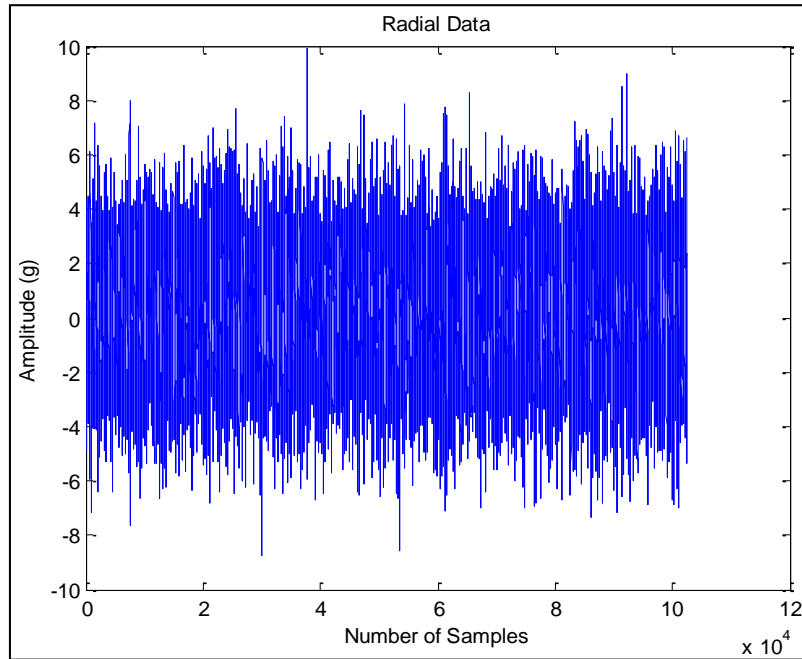
Figure 12. Example of radial raw data.

The second way to access the data is as follows:

1. Go to the directory or folder that contains the desire file.

2. Select the desire file by left-mouse click.

3. Drag and drop the file into the MATLAB Command window to open the data file.

At that point, one can follow previous steps or commands shown to plot or access the axial and/or radial data.

6. Conclusion

This technical note presented the data structure for seeded faults of helicopter oil cooler bearings. It described the data sets as well as how to access and plot the axial and radial raw data. The features of these test data sets will be described in future reports.

7. References

1. Impact's 1st Quarter Report, December 20, 2007 from Impact Technologies, LLC, under the contract number W911NF-07-2-0075.

2. Impact's Option 1, 3rd Quarter Report, November 30, 2009 from Impact Technologies, LLC, under the contract number W911NF-07-2-0075.

3. Impact's Option 2, 2nd Quarter Report, March 10, 2010 from Impact Technologies, LLC, under the contract number W911NF-07-2-0075.

4. Impact's Final Report for Option Phase II, September 10, 2010, from Impact Technologies, LLC, under the contract number W911NF-07-2-0075.

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         APG MD 21005

INTENTIONALLY LEFT BLANK.